Energy Strategy Reviews 32 (2020) 100541

Contents lists available at ScienceDirect

Energy Strategy Reviews

journal homepage: http://www.elsevier.com/locate/esr

Energy supply transformation pathways in Iran to reduce GHG emissions in line with the Paris Agreement

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ARTICLE INFO

Keywords:
Energy system of Iran
Energy transformation pathways
Energy modeling
GHG mitigation

ABSTRACT

Extensive dependence of the national economy on wasteful fossil fuel use as well as limited access to the international financial markets and the best available techniques over the strict economic sanctions period have hindered Iran from developing a sustainable energy system. By considering the reversal order, the present study investigated the least-cost options for improving energy efficiency and reducing GHG emissions in the energy supply sector. The essential purpose of this research work is to increase the evidence base necessary to inform policy and strategy discussions within Iran and related communities concerning the choice of GHG emissions reduction. Applying ARDL approach to project demand data besides running the bottom-up technology-rich optimization model of MESSAGEix over the 2016–2030 period help to tackle the transparency challenge of Intended Nationally Determined Contributions (INDCs) submitted by Iran. The research results suggest that improving the efficiency of fossil-fueled power plants to 46% besides curbing routine gas flaring by 2030 could well cover the Iranian unconditional and conditional contributions in the energy sector to cut GHG emissions by 12% compared to the business-as-usual pattern. Ensuring technical and financial supports, Iran can undertake the Intended Nationally Determined Contributions (INDCs) under the Paris Agreement, in line with the national policies to reduce energy intensity.

1. Introduction

The energy system in Iran is facing major challenges concerning sustainability. High rates of population and economic growth, urbanization, changes in lifestyle, and also subsidized supply of fossil fuels have contributed to rapidly increasing energy consumption over the past three decades [1–3]. Meanwhile, energy consumption has been growing at much higher rates than economic output, which led to the increasing trend of energy intensity in contrast to the declining trend that is experienced in most developed countries [4,5]. Energy-intensive economic growth besides carbon-intensive portfolio of primary energy supply placed Iran among the top ten greenhouse gas (GHG) emitters, while GHG emissions as a result of burning fossil fuels are supposed to be very likely the main anthropogenic driver causing climate change [6]. In addition to the global effects, the increasing use of fossil fuels besides compact urban development have also had adverse local environmental impacts, especially in mega-cities.

Energy-related projects are typically large, capital-intensive, with long pay-back periods, while their financing is a delicate task. Then, under-investment - the level of investment being lower than the economically efficient level - is a common challenge in the energy sector. This problem may lead to adverse consequences such as low supply capacity, unreliable supply, sub-optimal technology portfolio, costly demand provision as well as adverse environmental effects [7]. Regarding the energy system in Iran, restrictions on technology transfer and international financing support over the strict international economic sanctions period of 2011–2015 do even worsen the situation. The continuing trend of population and economic growth in the coming years seems to bring about severe challenges in providing energy demand securely.

Nevertheless, Iranian society may face many opportunities to develop a more sustainable energy system in the light of relaxed access to international financial services as well as new efficient technologies. Such a development pathway will also benefit neighboring countries through their post-war development and contribute to the common acts by global society against climate change. These all necessitate an in-depth study of the Iranian energy system to set investment and technology improvement priorities across the energy sector.

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https://doi.org/10.1016/j.esr.2020.100541
Received 1 March 2020; Received in revised form 17 June 2020; Accepted 9 August 2020
Available online 29 August 2020

The main objective of the present research is to identify priority actions to reduce energy and emission intensity of the energy supply system in Iran regarding the total costs. The outcomes of such an analysis help to clarify how Iran possibly will cover proposed GHG mitigation contributions towards the 2015 Paris Climate Agreement based on the principle of Common but Differentiated Responsibilities. This may tackle the transparency challenge of Intended Nationally Determined Contributions (INDCs) submitted by Iran in the context of the Paris Climate Agreement. To achieve the required outcomes, it needs to apply a bottom-up energy model. This may offer key insights into the implications of policies that can be pursued by the Iranian government to improve energy intensity and move toward developing a low-carbon society in a cost-efficient and effective way.

The bottom-up energy models could be applied both to the analysis of the entire energy sector or to the detailed study of a sub-sector. Large-scale models are used to assess energy and climate policies globally in different studies including the benchmark IPCC reports [8]. Besides, a new strand of literature has assessed the global impact of national climate policies by using a suite of integrated assessment models. The multi-model assessment approach adds to the robustness of the results. Among them is the study by Mark Roelfsema et al. who used nine integrated assessment models to assess the combined effect of national policies and NDCs for G20 economies regarding the temperature targets within the Paris Climate Agreement [9]. The study results showed that all countries have a considerable gap with optimal pathways towards well below 2° Celsius target.

In parallel, relevant bottom-up energy optimization tools have been applied for many national-scale studies on technical feasibility and economic costs of implementing energy/climate policies. Among them, A. Hainoun et al. [10] formulated optimal long-term energy supply strategy of Syria for the study period of 2003–2030; Md.A.H. Mondal et al. [11] examined the impacts of CO_2 emission reduction targets on future technology selection in Bangladesh power sector up to 2035; E. Assoumou and N. Maizi [12] provided consistent energy, emissions and carbon value estimates for France; P. Ekins et al. [13] tried to explore the cost and other implications of reaching both the medium- and long-term carbon reduction targets in UK; U.K. Rout et al. [14] provided long-term projections of future energy demand and associated carbon dioxide emissions for China; H.J. AlFarra and B. Abu-Hijleh [15] evaluated the effectiveness of the UAE's proposed nuclear energy strategy in mitigating carbon dioxide emissions in long-term; Md.A.H. Mondal et al. [16] examined the most cost-effective selection of future power generation technologies and assessed the co-benefits regarding carbon dioxide emissions mitigation for UAE; K. Vaillancourt et al. [17] defined and analyzed possible futures for the Canadian energy system tracking carbon dioxide, methane, and nitrous oxide emissions; M.S. Tsai and S.L. Chang [18] assessed Taiwan's low carbon development pathways; N. Victor [19] examined the impacts of shale gas supply and climate policies on U.S. energy security in five scenarios modeled with MARKAL; A. Gambhir et al. [20] explored the major technologies on which to focus future developments in order to achieve deep decarbonization in China; researchers from two Japanese institutes of RITE and NIES [21] analyzed the potential impacts of the Japanese INDC on the energy system; E. Guemene Dountio et al. [22] analyzed expansion of the electricity generation system and its emissions corresponding to three scenarios of electricity demand in Cameroon assuming different economic growth levels; C. Lenox and P.O. Kaplan [23] compared the carbon emission profiles of the U.S. energy system over a series of model runs with a range of upstream methane emission leakage rates; K. Vaillancourt et al. [24] tried to explore possible deep decarbonization pathways and identify priority actions for the Canadian energy sector which would allow Canada to participate in these global mitigation objectives; Md.A.H. Mondal et al. [25] identified alternative energy development pathways that meet Philippines' rising electricity demand while improving energy security, promoting access to reliable modern energy, and mitigating GHG emissions; A. Sadiqa et al. [26] presented an energy transition roadmap for Pakistan in which the total energy demand in long-term is met by electricity generated via climate friendly renewable sources; S.A. Ur Rehman et al. [27] provided economic details alongside environmental emissions (GHGs) pertaining to electricity demand, supply, and generation in Pakistan for the period 2015–2035; O. Balyk et al. [28] described design, input data, and usage of the first developed Danish energy system model that includes the complete national energy system; Md.A.H. Mondal et al. [29] assessed the most cost-efficient energy development pathways that meet Egypt's rising electricity demand while mitigating GHG emissions; and, A. Chiodi et al. [30] evaluated the technical feasibility of an 80% GHG emissions reduction target for Ireland. Based on the cumulative emission budgets to be compliant with the Paris Climate Agreement targets, P.R.R. Rochedo et al. [31] explored different scenarios to evaluate the effort needed in the energy sector of Brazil to compensate for the weakening of environmental governance; and, H. Wang et al. [32] assessed the impact of early and delayed mitigation efforts for China's power sector.

In addition to the national-scale studies, researchers developed bottom-up optimization models to analyze how various energy and climate measures can transform the states and cities into low-carbon communities. For example, A. Lind and K. Espegren [33] tried to explore the energy consumption path in Oslo, Norway and found optimal ways of reducing the CO2 emissions; D. McCollum et al. [34] analyzed the feasibly of achieving deep emission reduction goals defined by California policy makers.

Regarding the energy system of Iran, few studies have been carried out in recent years. Sadeghzadeh [35] examined economically optimal technology portfolio and fuel share in the building subsector for 25 years. Likewise, Sadeghi and Mirshojaeian Hosseini [36] investigated the least cost technology portfolio and also fuel share in the transportation subsector for 25 years. Amirnekooei et al. [37] evaluated the effects of applying different demand and supply-side strategies on energy consumption and GHG emissions in four scenarios for 25 years. Moshiri et al. [38] projected the energy demand of households, manufacturing industries, transportation, and other subsectors in three alternative scenarios for the 2010–2030 period. Aryanpur and Shafiei [39] assessed the lowest cost technology options for power generation under different circumstances characterized by fossil fuel price as well as carbon tax from 2015 to 2045. Eshraghi and Ahadi [40] looked at the transformation path for petroleum refining and power generation subsectors considering existing and most likely future technologies from 2012 to 2035. Sahabmanesh and Saboohi [41] developed a model representing the flow of energy from resources to end-use technologies for sustainability assessment of the energy system in Hamedan province for the 2015–2050 period. Furthermore, Mirzaei and Bekri [42] projected energy consumption and CO_2 emissions over the 2000–2025 period using system dynamics modeling approach. However, a comprehensive energy assessment using accredited energy modeling tools is currently lacking in the case of Iran. These tools could support long-term energy policy development, clarify current INDCs, and propose more ambitious contributions.

The current research work is based on a bottom-up analysis of the energy supply system in Iran. The results offer detailed insights on approaching reduced energy and emission intensities in the energy supply-side. This may help national authorities in preparing short-to medium-term low carbon development strategies of the energy sector and would also clarify the measures regarding the intended contributions by Iran to reduce GHG emissions under the Paris Climate Agreement. The key purpose of this research work is to increase the evidence base necessary to inform policy and strategy discussions within Iran and related communities concerning the choice of GHG emissions reduction target for 2030.

The rest of the present paper is organized as follows. Section 2 presents the methodological approach of the study, proposed scenarios as well as underlying assumptions. Section 3 proceeds with an overview of the main results and a discussion on the policy implications. Finally, section 4 concludes with a summary of key insights and pointing out directions for future research.

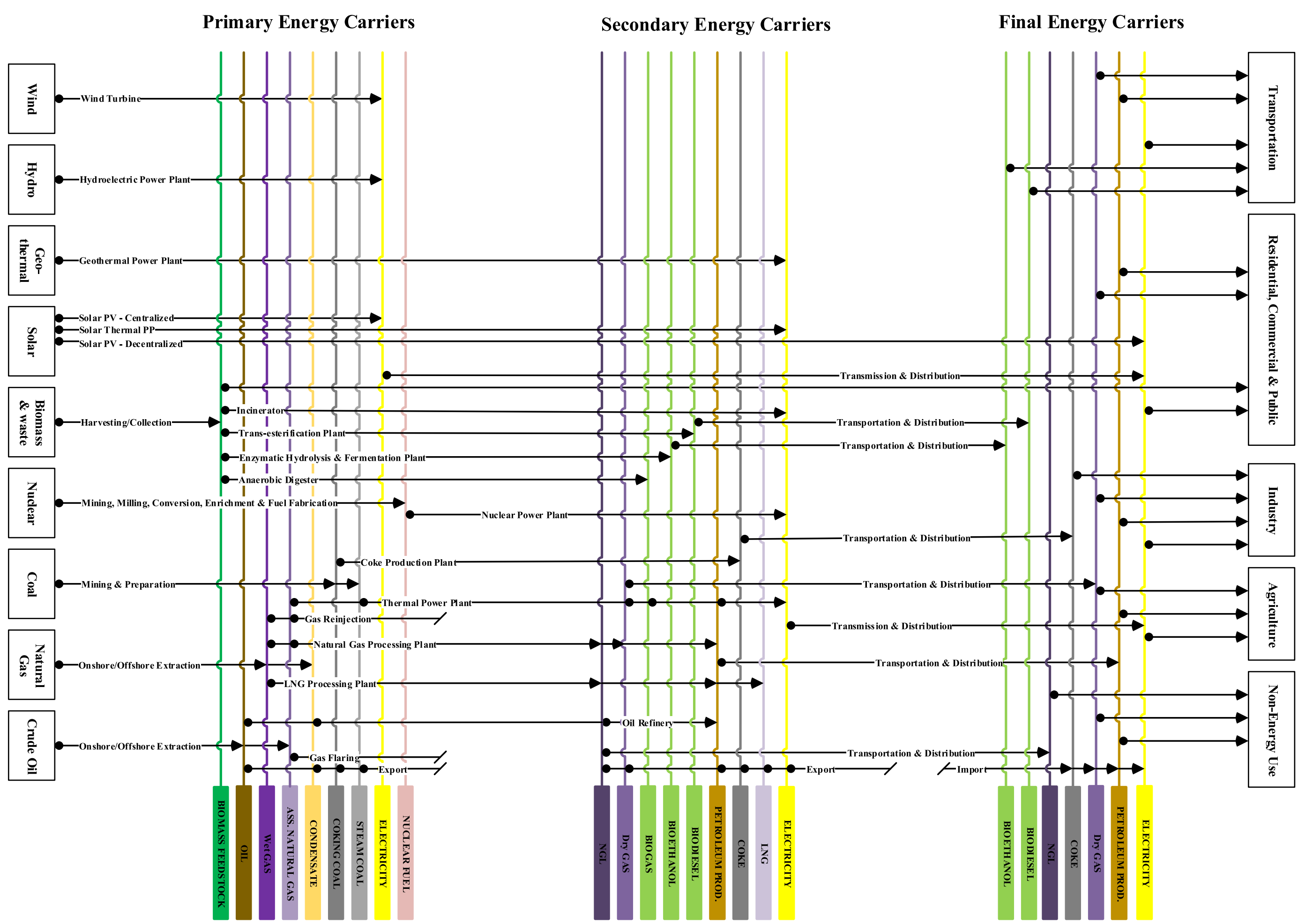

Fig. 1. The reference energy system from primary to final energy carriers.

2. Materials and methods

Energy modeling is a common practice for evaluating the behavior of energy systems and formulating appropriate policies for developing a sustainable energy sector. A thorough review of energy models by Jebaraj and Iniyan [43], Urban et al. [44], Connolly et al. [45], Bhattacharyya and Timilsina [46], Wilson et al. [8], and Laha and Chakraborty [47] indicates that there are various classes of energy models which differ from each other in terms of methodology, applications, and scope. Furthermore, there is no single ideal tool to address all issues related to energy systems. Therefore, applying any model is specific to the particular objectives of research activities [48]. Bottom-up and top-down modeling are two main approaches for energy and climate analysis. While bottom-up models refer to the focus on the detailed analysis of energy technologies, top-down models use macroeconomic data to determine the development of energy prices and demand/supply. As technological changes are among influential factors, even the most important one on the energy supply system according to different studies [49], applying a bottom-up energy optimization model will benefit the most regarding the research purposes.

To pursue the objectives of the current study, MESSAGEix (Model of Energy Supply Systems Alternatives and their General Environmental Impacts) was applied for the first time to analyze the energy system in Iran. MESSAGEix is a dynamic bottom-up linear/mixed-integer optimization model used for medium-to long-term energy planning and policy analysis. The latest version of the model lets the user access the mathematical formulation to be able to include all the features related to the particular objectives of the research activity. It does also present innovative approaches to the problem formulation [50]. This was the main reason to apply MESSAGEix in the current study. It was originally developed at the International Institute for Applied Systems Analysis (IIASA) over the last four decades and used for many scientific studies in global, regional, country, and even local levels [50]. The most well-known studies among them are the Global Energy Assessment report [51] and the Fifth Assessment Report of the IPCC as well as earlier reports [52].

MESSAGEix seeks to optimize the energy system with given energy demand levels by commodity at minimal total costs discounted to the reference year. Total costs refer to the sum of investment costs, fixed and variable operation and maintenance (O&M) costs, including resource extraction costs, import costs, export revenues, and related external costs. For a particular technology, its capacity remains active until the end of its technical lifetime; in case the lifetime of the technology goes beyond the modeling horizon, its salvage value is deducted from the objective function. Total discounted energy system costs are minimized subject to the technological, environmental, and economic constraints over the planning horizon of the model. The basic constraints of the model take into account the followings: (1) meeting final energy demands; (2) the utilization of non-renewable and renewable energy resources; (3) the balance for every energy carrier at different levels of the energy system; (4) the bound on energy conversion and utilization due to installed capacities; (5) the capacity transfer between successive periods and the capacity expansion due to investment; (6) the limits on emissions of various pollutants imposed on the system for environmental reasons; and (7) various other technological constraints representing the complex interconnections and ruling regarding the system parts involved. The full technical documentation of the MESSAGEix model is available in a paper by Huppmann et al. [50].

The main result of the MESSAGEix model is the optimal configuration of the energy system. This is done based on the reference energy system concept, which proposes the energy system chain. MESSAGEix considers the energy system with all its interdependencies from resource utilization to the provision of final or useful energy demand, through the reference energy system as the conceptual model.

2.1. Reference energy system

The reference energy system for Iran is developed to be used as the conceptual model of the present research work (Fig. 1). The reference energy system captures different technologies connected through energy/material carriers in different levels from energy resources to primary, secondary, and final/useful energy. Energy carriers are represented as vertical lines connected via interlinking horizontal lines as different technologies that make changes in inputs to yield outputs. A set of inputs may be fed to the intended technology to return another set of outputs. Inputs and outputs are specified in Fig. 1 by points and arrows, respectively. The current modeling practice intended 38 technologies and 36 energy carriers within a single node.

Technologies are in 5 different groups. First, there are extraction/mining/utilization technologies to exploit non-renewable and renewable energy resources. They include wind turbine (wind farm), hydroelectric power plant (in both small and large scales), geothermal power plant, solar PV (grid-connected centralized), solar thermal power plant (concentrated solar power), harvesting or collection of biomass resources (agricultural residue, municipal solid waste, and animal waste), uranium mining and milling, coal mining and preparation as well as both onshore and offshore extraction of natural gas and crude oil.

Technologies of the second group are treatment and conversion technologies proposed to yield secondary energy carriers in desired forms (secondary energy carriers come from the transformation of primary or other secondary energy carriers). This group of technologies consists of waste incinerator, *trans*-esterification plant, enzymatic hydrolysis, and fermentation plant, anaerobic digester, processing of nuclear fuel, nuclear power plant (light water reactor and advanced light water reactor), coke production plant, gas reinjection, gas flaring (as well as different flare gas recovery technologies), gas processing plant, LNG processing plant, oil and condensate refineries as well as different thermal power plants (subcritical steam coal-fired, supercritical steam coal-fired, integrated gasification combined cycle, gas turbine, steam turbine, combined cycle gas turbine, and expansion turbines). Oil refineries could be of topping, hydro-skimming, and conversion types. While topping refineries are limited to the basic distillation units, hydro-skimming refineries allow producing a full range of refined products. Besides, conversion refineries, also called cracking refineries, allow converting heavy cuts into lighter products including gasoline [5,53].

Third, transportation/transmission and distribution technologies are considered as means of delivering energy carriers to the end-users (waste energy recovery from natural gas distribution network via pressure recovery turbines was also proposed to produce electricity).

Fourth, there is an import/export possibility of coal, oil, condensate, petroleum products, natural gas, NGL (Natural Gas Liquids), coal, and electricity. Different capacities are proposed for imports and exports of energy carriers in different scenarios. Fifth, end-use technologies are applied to deliver energy services; however, the current study takes the final energy demand volume estimated through an econometric model and does not assess the end-use technologies in detail.

The technical and economic characteristics of available and future technologies considered in the current study are taken from annual reports of the Iranian Ministry of Petroleum [5] and the Ministry of Power [4] as well as the Scenario Database of Shared Socioeconomic Pathways (SSPs) [54]. To have an overview of the input data to the model, technical and economic parameters regarding the power generation sector is presented in Appendix A.

2.2. Model time horizon

Regarding the purpose of the study to uncover the initial contributions of Iran within the Paris Climate Agreement, the model covers the time interval of 1975–2035. All the time steps are in 5 years except for the 2011 to 2015 period, which are in single year steps with sufficient and reliable data. The planning horizon extends from 2015 to 2035. The first modeling year is 2015 to calibrate and verify whether the optimization results are consistent with the actual situation or not. Besides, there are available historical data for the time interval of 1975–2014.

The model computes the total net present value (NPV) of periodic cost streams over the planning horizon that are discounted to the reference year of 2015 by 10% as the Social Time Preference Rate (STPR). It seems reasonable due to the variety of existing risks and uncertainties in developing countries like Iran. Moreover, the results for the ending five years period of study from 2031 to 2035 was exempted from detailed analysis because of the probable modeling distortions in the terminating time step.

2.3. Energy demand pattern

Energy demand forecasting could be done through different methods [55–57], mainly econometric and end-use accounting [58]. Generally, energy-related decisions in the end-use level of the energy system do not tend to follow the cost-minimizing rationale [48]. Also, available data for technologies used by end-users is insufficient, especially for developing countries. So, the econometric approach was applied to project carrier- and sector-wise final energy demand in this paper. Further, national policies and priorities were interpreted to complete projection practice as for the (energy and non-energy use) demand forecast in the petrochemical sector [59]).

The first step in the econometric analysis is to examine stationary of time series data (the aggregated data are presented in Appendix A). The Augmented Dickey-Fuller (ADF) test was applied to check the unit root property. Besides, the Kwiatkowski, Phillips, Schmidt, and Shin (KPSS) method was used to verify the results obtained from the ADF test. While ADF tests the null hypothesis of a unit root process, the KPSS method has a null hypothesis of stationary. Running these tests showed that some series are integrated of order zero, I (0), and others are integrated of order one, I (1). Considering the mixed nature of stationary for variables of interest and the small number of available observations, the error-correction representation of an autoregressive distributed lag model (ARDL) specification seems to be an appropriate choice. This specification is proposed to capture both short-and long-run dynamics of the annual energy demand as follows [60–62]:

$$\Delta(Lfed_{e,s,t}) = c + \sum_{i=1}^{i=p} \alpha_i \Delta(Lfed_{e,s,t-i}) + \sum_{i=0}^{i=q} \beta_i \Delta(Lupr_{t-i}) + \sum_{i=0}^{i=q} \gamma_i \Delta(Lthh_{t-i}) + \sum_{i=0}^{i=q} \omega_i \Delta(Lgdp_{s,t-i}) + \alpha' Lfed_{e,s,t-1} + \beta' Lupr_{t-1} + \gamma' Lthh_{t-1} + \omega' Lgdp_{s,t-1} + \theta\, dum_t + \varepsilon$$

While $fed_{e,s,t}$ is the demand for final energy type e in sector s at time t (per capita in some cases), $fed_{e,s,t-i}$ is the (i-times) lagged amount. This is also the case for other variables, including upr_t representing the urban population rate, thh_t representing the total number of households, and $gdp_{s,t}$ representing total GDP per capita or sector-wise value-added. The stated equation is the general one and the drivers for changes in energy demand of different sectors are selected based on similar experiences [14,63,64]. Besides, a dummy variable is used to net out the impermanent impacts of the gasoline rationing plan of 2007 and the subsidy reform plan of 2010. Logarithms for variables (except the dummy one) were taken and Δ sign expresses the first difference operation.

The model incorporates first-order lagged level variables and a maximum of two-times lagged differential terms given the small sample size. After developing different models, regressors were checked for multicollinearity as it increases the standard errors of the coefficients. One method to measure multicollinearity is the variance inflation factor (VIF), which assesses how much the variance of an estimated coefficient increases if the regressors are correlated. If the VIF for a predictor is near or above 10, removing highly correlated regressors fixes the multicollinearity problems.

Then, the full scope of pre-selected variables was examined iteratively using stepwise regression. The applied approach for model selection in this paper performs multiple iterations by dropping one regressor at a time. In each iteration, the variable that gives the minimum Akaike information criterion (AIC) when dropped is thrown down for the next iteration until there is no significant reduction in the AIC. In other words, given a collection of models for the given data, AIC is used to evaluate the quality of each model relative to the others.

The next step is diagnostic checking of the selected models for normal residuals, homoscedasticity, serial correlation, and significance. Diagnostic checking was done using the Shapiro–Wilk test for normality, Breusch-Pagan (BP) test against heteroskedasticity, and Breusch–Godfrey LM test for serial correlation. If all the tests passed, the ordinary least square (OLS) estimates would be asymptotically normally distributed. The current study applied R Programming Language for all the data analytics.

By assuming final energy consumption to be equal to the final energy demand, the models were estimated using annual final energy consumption time-series data of the 1988–2015 period. The historical data for consumption of different energy carriers in the end-use sectors are available in the annual reports of the Iranian Ministry of Petroleum and the Ministry of Power [4,5].

Following assumptions were made to have a better estimation of energy demand functionality:

i) for the transportation sector, gasoline equivalents of annual CNG (Compressed Natural Gas) and LPG (Liquefied Petroleum Gas) consumption were added to the annual gasoline consumption. Then, the total amount of derived gasoline consumption was estimated through the time-series models. The share of CNG is projected to keep up at the 2014–2015 level. Moreover, the share of LPG will drop gradually to reach almost zero in the model time horizon;
ii) similar to the transportation sector, total consumption amounts of LPG, kerosene, diesel, fuel oil, and natural gas were estimated for residential, commercial, and public sectors as well as industry. Then, the demand for every energy carrier type was projected using the shares of different types based on existing and future state-based policies. The most regarded policy was to increase the share of natural gas in the final energy use basket;
iii) as regards the agriculture sector, electricity use of electric water pumps accounts for a significant share of total electricity consumption. Then, the electricity (and diesel) demand increase (and decrease) in this sector was projected based on likely numbers of electric water pumps, which will be substituted for diesel-powered water pumps in the model time horizon. Also, the total consumption of diesel, kerosene, fuel oil, and natural gas were estimated for the agriculture sector, while the demand for every energy carrier type was projected using their changing shares to the total consumption;
iv) electricity demand in other sectors was projected separately.

Based on assuming an annual GDP growth rate of 4.5% over the model time horizon (as the long-term average value), total population to grow from around 80 million in 2014 to almost 89 million in 2030 with a decreasing growth rate [65], urban population rate to reach 79% in 2030 from 73% in 2014 [66], and average household size comes down to 3.02 in 2030 from 3.54 in 2014 [67], Table 1 presents the average annual projection data for the final energy demand of different energy carriers in sequential periods over the model time horizon.

However, it was not possible to come in a valid model for projecting jet fuel demand. Then, a simple univariate autoregressive integrated moving average (ARIMA) model is utilized as an alternative. ARIMA approach allows each variable to be explained by its own lagged values and error terms.

Table 2 presents the growth rate for electricity, natural gas, and total final energy demand from 2001 to 2030 in 5-years periods. The rates are decreasing and flattening. The declining growth rate of the total population and urbanization are among the influencing factors.

To introduce electricity demand fluctuations and considering the reliability of power generation from renewable resources, formulations based on the study by Sullivan et al. [68] are used. It ensures electric sector reliability through building sufficient capacity to meet the normal peak load levels and also having a heterogeneous mix of power plants so that they can serve different demand levels and react to changes in load. The annual average load factor of 0.65 is applied to the Iranian electrical grid [69].

2.4. Scenarios

Limited access to the best available techniques as well as insufficient energy investment, specifically in the period of 2011–2015, have had adverse effects on developing a sustainable energy system in Iran. The state has even failed to implement nationally ratified laws and regulations, especially regarding the communicated policies on energy intensity reduction. Considering the common will among different nations to tackle climate change, Iran may accompany by utilizing more efficient technologies with lower capital costs through energy transition; however, such a technology transition in the context of a developing country requires state intervention to leapfrog the technological ladder [70]. This is one of the reasons why the current study did focus on the technological transition in the energy supply-side that is mainly state-owned in Iran.

Relaxed international financing besides advanced technology diffusion to implement the laws and regulations on books are the main ideas behind defining two different scenarios to investigate the possible

Table 1
The energy demand projection (in MMBOE).

Energy carrier	2015	2016–2020	2021–2025	2026–2030
Electricity	133.8	150.8	174.7	201.1
Fuel oil	16.6	15.0	15.0	15.0
Gas oil	152.0	174.9	191.6	217.1
Gasoline	142.5	199.2	258.4	291.8
Jet fuel	9.8	11.2	13.6	16.4
Kerosene	19.2	14.9	9.4	5.9
LPG	15.1	15.4	15.2	15.2
Natural gas	619.3	768.5	1002.2	1238.8
Coking coal	7.7	8.2	9.0	10.0

Table 2
The demand growth rate for electricity, natural gas and total final energy (in %).

-	Electricity	Natural gas	Total final energy
2001–2005	7.4	9.6	5.2
2006–2010	7.0	11.4	6.1
2011–2015	5.1	5.9	2.1
2016–2020	4.2	7.1	5.3
2021–2025	3.0	5.4	4.5
2026–2030	2.9	3.5	3.0

transformation pathways in the supply-side of the energy system in Iran. The first scenario is "policies-on-ice" which reflects the continuation of observed trends during the decade before the planning horizon regarding limited investment on energy efficiency improvement and utilizing aging inefficient technologies (in such a manner, the policies-on-ice scenario is similar to the business-as-usual pattern). Therefore, capital market constraints and also friction over technology transfer restrain the development of a more efficient energy system in the policies-on-ice scenario [71]. Moreover, there is no strict enforcement of implementing national policies and plans.

The second scenario is "policies-in-hand." In contrast to the policies-on-ice scenario, frictionless technology diffusion as well as unlimited cost-effective investment in energy efficiency improvement are anticipated in the policies-in-hand scenario. This scenario assumes putting current state policies and plans on energy efficiency improvement in effect. The main plans are: improving complexity index of the oil refineries through adding secondary processing units (to lower the fuel oil yield to 10% by 2025 according to the law on Improving Energy Consumption Pattern, article 59); the full capacity utilization of condensate refineries which yield more higher-value product of gasoline (developing Persian Gulf Star Refinery with a processing capacity of roughly 360,000 barrels of gas condensate per day); efficient power generation through unlimited utilization of combined cycle power plants and the possibility to add steam power units to the currently working simple cycle gas turbines (increasing the efficiency of thermal power plants to 45% by 2014 according to Targeted Subsidy Reform Act, article 1); lower shares of liquid fuels in power generation because of the limitless access to natural gas; reduced loss in transmission/transportation and distribution of energy carriers (according to the Improving Energy Consumption Pattern law and Targeted Subsidy Reform Act); the possibility of utilizing gas pressure recovery turbines instead of throttling valves (according to the law on Improving Energy Consumption Pattern, article 46); as well as capturing fugitives and reduction of gas flaring through gas processing or power generation (to curb gas flaring to 10% or lower by 2021 according to the sixth 5-years development plan, article 48) [72].

The study considers main greenhouse gases including carbon dioxide (CO_2), methane (CH_4), sulfur dioxide (SO_2), and nitrogen oxides (NO_x). Since relevant national emission factors are not available, Tier 1 emission factors of guidelines by the Intergovernmental Panel on Climate Change (IPCC) have been adopted [73–75]. The study moves further comparing (expanded upon) other studies through calculating detailed emission volume in different levels of the energy system.

Regarding power generation, it is assumed that all the existing power plants will continue to work throughout the whole of their technical lifetime. Considering this assumption is particularly valid regarding the energy system in Iran as even very old power plants are kept in working condition with necessary maintenance and minor furnishing. The 65 MW planned coal-fired power plant that is expected to be installed by the state in the next five years is exogenously introduced into the model.

Moreover, the technical potential of grid-connected solar PV, wind, hydro, geothermal, and biomass-based incineration power plants are considered to be 50,174 MW, 4614 MW, 550 MW, and 566 MW, respectively [39,76,77]. Also, the potential of biogas generation is approximately 10 GW [78]. The installed power generation capacities of solar PV, CSP, waste incineration, and biogas units are permitted to grow up at a maximum rate of 20% and wind power at a rate of 30% annually during the study period.

Iran's annual crude oil export in the period 2012–2015 amounted to the average level of 1.08 from 2.2 million barrels per day in 2010. By relaxing the Iranian oil export and getting the foreign investment back to Iran's upstream oil industry, the export volume may catch up to about 2 million barrels per day in the policies-in-hand scenario. Accordingly, oil export volumes will be 1 and 2 million barrels per day, in the policies-on-ice and policies-in-hand scenarios, respectively. Similarly, the total net export of natural gas will reach 180 billion cubic meters per day in the policies-in-hand scenario against zero net trade in the policies-on-ice scenario [5]. Net trade of electricity is supposed to be zero in both scenarios based on available transmission capacities and electricity prices in the region. Moreover, gas volume for reinjection purposes assumed to be flat at 80 mcm per day in both scenarios in the course of the model time horizon.

3. Results and discussion

This section describes the underlying transitional changes featured on the supply-side of the energy system in the proposed scenarios. Energy scenario analysis focuses not only on the best estimates on the future pathways under different policies but it also provides guidelines for required changes in the energy system to achieve certain energy efficiency and climate targets [79].

3.1. Total primary energy supply (TPES)

The average annual TPES in the 2011–2015 period was 1908 MMBOE. The model results indicate that the average annual TPES will reach to 3491 and 3141 MMBOE by 2026–2030 period, in the policies-on-ice and policies-in-hand scenarios, respectively (Fig. 2). Over the 15 years of 2016–2030, the cumulative potential primary energy supply savings of utilizing more energy-efficient technologies in the policies-in-hand scenario comparing to the policies-on-ice scenario may well exceed 3215 MMBOE. While the average TPES increase in the 2001–2015 period was 5.10%, the increasing rate will drop to 4.11% and 3.38% by the 2016–2030 period in the policies-on-ice and policies-in-hand scenarios, respectively.

According to the model results, the economy-wide energy intensity, measured as the total primary energy supply per unit of gross domestic product, may experience a decreasing trend in the policies-in-hand scenario over the model horizon. The average annual energy intensity value over the 15 years of 2001–20015 was 2.9 BOE per million Iranian Rials (constant 1376 IRR). Meanwhile, the results show that the average annual energy intensity in the policies-on-ice scenario will go up to 3.1 BOE per million IRR in the ensuing 15 years of 2016–2030; but, it will

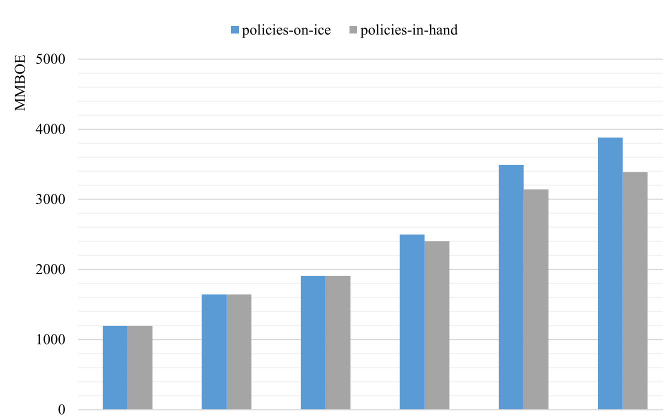

Fig. 2. The total primary energy supply in 5-years periods.

Table 3
Total installed capacity of different power plants by 2015 (in MW).

STPP	GTPP	CCPP	Nuclear PP	Hydro PP	Solar PV PP	Wind Farm	Other plants	Total
15,829	26,870	18,493	1020	11,354	9	159	451	74,185

drop to 2.8 BOE per million IRR over the same period in the policies-in-hand scenario. The decreasing energy intensity trend in the policies-in-hand scenario stems mainly from energy efficiency improvement in the power and refining sectors in addition to the reduction of gas flaring.

The model results demonstrate that the oil and natural gas will still provide the bulk of primary energy supply in both scenarios. Meanwhile, the share of natural gas in the total primary energy supply will increase from around 59% in the 2001–2005 period, to 78% and 80% by the 2026–2030 period, in the policies-on-ice and policies-in-hand scenarios, respectively (Fig. 3). As a relatively clean energy carrier, the share of natural gas in the total primary energy supply basket was steadily increasing over the past twenty years. The greater share of natural gas out of the total primary energy supply in the policies-in-hand scenario is mainly due to the timely-investment in new gas production capacity as well as the fuel switching in power generation from liquid fuels to gas.

In 2015, around 12 bcm (82 MMBOE) of gas was flared roughly equivalent to the total gas consumption of a medium-sized European country. While the flaring will slightly continue to rise in the policies-on-ice scenario, it will be prevented up to 90% by 2025 and afterward in the policies-in-hand scenario (curbing routine gas flaring). By tackling the flaring and leakage problems of utilizing natural gas, natural gas could play its role as a bridge fuel in the ongoing energy transition regarding the increasing share of natural gas in the TPES basket.

3.2. Refining

Iran has predominantly been a net refinery products' exporter; however, the country has been dependent on gasoline imports to meet domestic demand. This is mostly because of the inefficient refining pattern in aging country-wide refineries.

Against ambitious plans to increase refined gasoline production yield and to halt imports of this fuel, the expected improvement in the refining pattern of the domestic refineries was slow mainly due to the financial and technological restrictions. While the production yield of gasoline in the policies-on-ice scenario will gradually increase from the average level of 20.1% in the 2011–2015 period to 27.9% by the 2026–2030 period, it can upsurge to more than 37.3% by the same time in the policies-in-hand scenario (Fig. 4). Accordingly, the fuel oil yield of the oil refineries will reach 17% and 10% by the 2026–2030 period in the policies-on-ice and policies-in-hand scenarios, respectively. It shows that pursuing the policies-in-hand scenario will be successful in meeting the targeted plans.

While the country will be self-sufficient in gasoline by the middle of the 2016–2020 period in the policies-in-hand scenario, gasoline imports in the policies-on-ice scenario may increase to about 19 MMBOE in the 2026–2030 period of the average level of 13.244 MMBOE over the 2011–2015 period. Otherwise, restrictions on gasoline imports may cause Iran to replace poor quality and high-cost petrochemical gasoline with imported gasoline.

The results show that higher gasoline production yield in the policies-in-hand scenario will be possible through the utilization of new condensate refining complexes with a capacity of 360,000 barrels of gas condensate per day, which yields a lot more gasoline than other products. Moreover, the addition of Residue Fluid Catalytic Cracking Units (RFCCUs) to the current refining plants, with a total installed capacity of 226,287 barrels of heavy cuts per day by 2030, significantly increases the yield of higher-value products like gasoline and diesel from a barrel of crude. Launching new Persian Gulf Star condensate refinery in the policies-in-hand scenario will eradicate gasoline imports from the middle of the 2016–2020 period. Unlike the policies-in-hand scenario, the launch of the Persian Gulf Star condensate refinery is expected to be delayed and start-up in 3 phases by 2025 in the policies-on-ice scenario.

Doing some extra modeling practices show that the average gasoline production yield of around 40% is a balancing point to provide both gasoline and diesel demand by the country-wide refineries. Then, a higher average gasoline production yield is not expected in any scenario.

3.3. Power generation

Table 3 presents the total installed capacity of different power plants by 2015. Without any demand-side management measures in action to reduce the absolute electricity demand levels and shave peak load, the total installed capacity of power plants will amount to around 99 GW similarly in both scenarios by the 2026–2030 period; however, the share of different technologies out of total installed capacities are different in two scenarios. Retaining extra capacity based on the introduced equations to the model helps to cover the peak load of electricity.

According to the model results, total electricity output in the policies-in-hand scenario is lower compared to the other scenario (389,721 against 401,478 GWh) because of the reduced power transmissions and distribution loss in this policies-in-hand scenario. While the aggregated output of nuclear, hydro, and other renewable power plants are similar in both scenarios, the fossil-fueled power output out of the total power output will almost reach to 94.2% and 93.9% by the 2026–2030 period in the policies-on-ice and policies-in-hand scenarios,

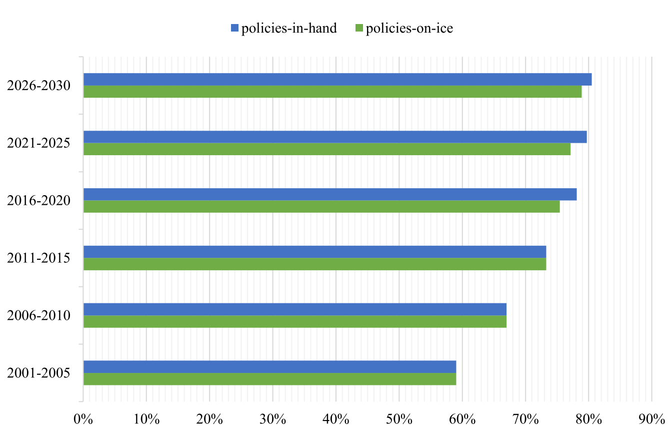

Fig. 3. The share of natural gas out of the total primary energy supply in 5-years periods.

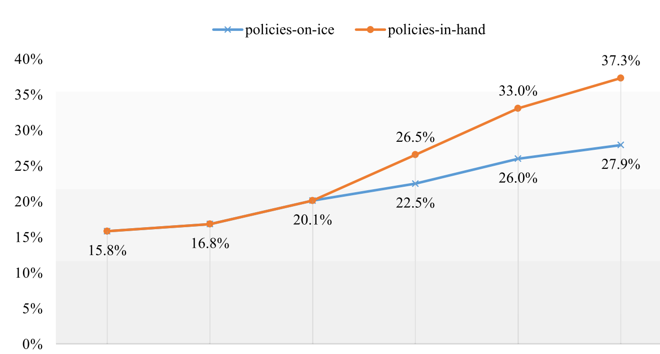

Fig. 4. The average gasoline production yield of refineries in 5-years periods.

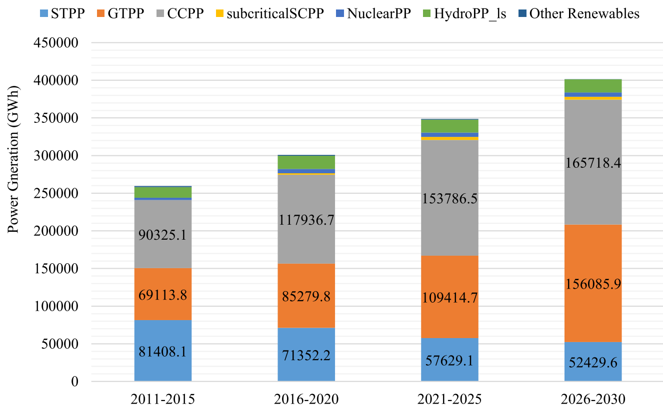

Fig. 5. The power generation mix in the policies-on-ice scenario in 5-years periods.

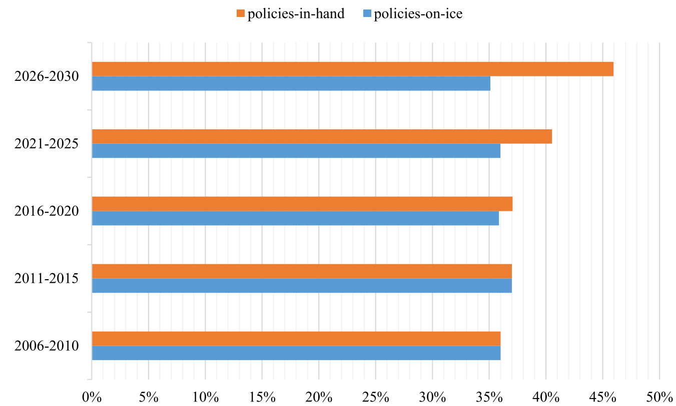

Fig. 7. The average energy efficiency of fossil-fueled power plants in 5-years periods.

respectively. Different shares arise from utilizing gas pressure recovery turbines (amounting to 6311 GWh over the 2026–2030 period) besides early decommissioning of the coal-fired power plants in the policies-in-hand scenario.

Fig. 5 and Fig. 6 illustrate the power generation mix in two scenarios of policies-on-ice and policies-in-hand, respectively. The evolution of the power sector over the model time horizon varies markedly across the two scenarios. While the new capacity development of capital intensive Combined Cycle Power Plants (CCPPs) in the policies-on-ice scenario is limited according to the trend observed during the decade before the planning horizon, this type of high-efficiency power plant will be the main contributor to the power generation in the policies-in-hand scenario. Meanwhile, the contribution of aging and low-efficiency Steam Turbine Power Plants (STPPs) will shrink in both scenarios. Furthermore, the installation of new subcritical steam coal-fired power plant (subcriticalSCPP) in both scenarios is exogenously forced consistent with the local potential of utilizing heating-coal and also the already 650 MW planned power plant to launch in the 2016–2020 period.

The addition of Heat Recovery Steam Generators (HRSGs) and steam turbines to the existing Gas Turbine Power Plants (GTPPs), also known as repowering process, as well as utilizing new high-efficiency CCPPs in the policies-in-hand scenario will improve the conversion efficiency of fossil fuels to power up to around 46% by the 2026–2030 period from the average level of 37% in the 2011–2015 period (Fig. 7). The efficiency level in the policies-in-hand scenario is compliant with the national policy targets mentioned before.

As a result, the 15 years cumulative consumption of fossil fuels to meet the electricity demand in the policies-on-ice scenario will be 37% greater compared to the policies-in-hand scenario from 2016 through 2030. The significant energy saving potential in the policies-in-hand scenario stems from improved conversion efficiency of fossil-fueled power plants and also the reduction of losses in the transmission and distribution of power. This does suggest that energy efficiency improvement of the power system in Iran is of utmost priority. Lack of energy planning and making wrong decisions regarding the development of power capacity expansion may cost a lot to the energy sector [80].

In line with the policy by the Ministry of Petroleum to increase the share of natural gas in the power sector, the share of liquid-fired power plants will fall sharply in the policies-in-hand scenario leading to less polluting power generation pattern; but, the share of liquid fuels used for power generation in the policies-on-ice scenario will continue to be 10% by the 2026–2030 period.

3.4. GHG emissions

The model results show that the emission (carbon) intensity of energy consumption in the policies-in-hand scenario may be reduced by 10% over the model time horizon; however, the suboptimal development of the energy system in the policies-on-ice scenario will prevent the emission intensity from declining over the model time horizon.

Fig. 8 represents the annually average energy-related GHG emissions (totally from burning fossil fuels and fugitive emissions) in two scenarios over the model time horizon compared to the average annual emissions level of the 2011–2015 period. Considering the CO_2eq of every GHGs, Table 4 presents the share of different GHGs from the total emission level in both scenarios.

Emissions of all energy-related GHG by the 2026–2030 period, will

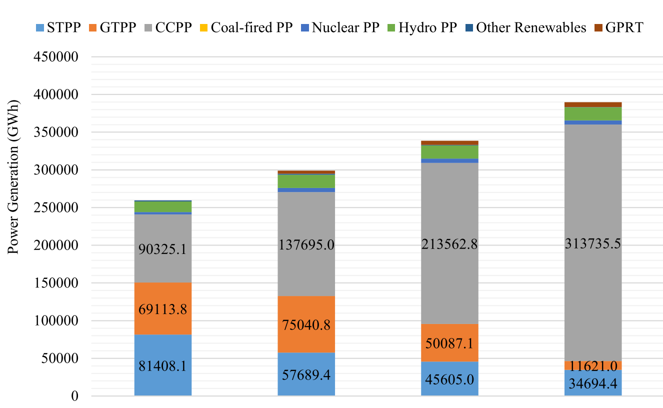

Fig. 6. The power generation mix in the policies-in-hand scenario in 5-years periods.

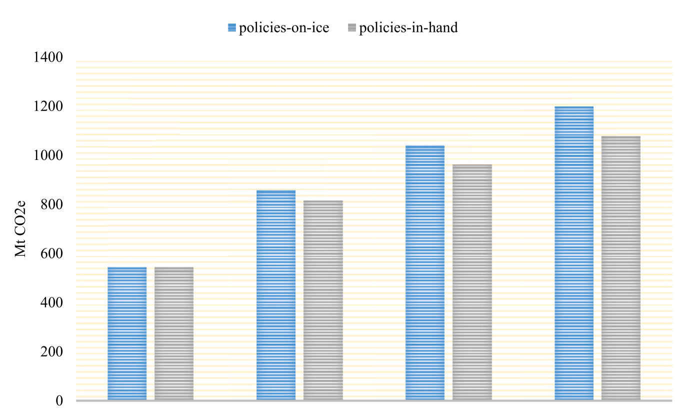

Fig. 8. The total annual GHG emissions from the energy sector in 5-years periods.

Table 4
Share of different GHGs from total energy-related emissions in the 2026–2030 period (in %).

Scenarios	CO2	CH4	N2O	Fugitives	Flaring (CO2eq)
policies-on-ice	92.19	0.19	0.28	4.05	3.30
policies-in-hand	94.90	0.19	0.28	4.53	0.10

grow to less than 1078 million tons of CO_2eq in the policies-in-hand scenario comparing to 1198 million tons of CO_2eq in the policies-on-ice scenario. Taking the average level of GHG emissions over the periods of 2026–2030 and 2031–2035 as an estimate of total GHG emissions in 2030, and also considering the significant share of energy-related GHG emissions out of total GHG emissions in Iran [81], the reduction potential of GHG emissions in the policies-in-hand scenario over the policies-on-ice scenario is almost comparable to Iran's totally unconditional and conditional target to cut GHG emissions. A 4% cut in emissions by 2030 relative to the business-as-usual pattern and 12% cut conditional on international support are proposed in the Iranian Intended Nationally Determined Contributions (INDCs) along with the Paris climate Agreement achieved at COP21.

The lower level of GHG emissions in the policies-in-hand scenario compared to the policies-on-ice scenario is mainly associated with two factors: (1) efficiency improvement of fossil-fueled power plants and also replacing liquid fuels by natural gas to burn, and (2) curbing gas flaring. In 2030, the average annual contribution of these two factors to the energy-related GHG emissions reduction in the policies-in-hand scenario compared to the policies-on-ice scenario will be 82 and 40 million tons of CO_2eq, respectively. Considering the estimated potential reduction of GHG emissions by 2030 to be around 140 million tons of CO_2eq in the policies-in-hand scenario compared to the policies-on-ice scenario, proposed improvement measures in power generation and gas flaring could together cover the INDCs by Iran regarding the energy sector.

Decreased upstream activities as a result of lower fossil fuel consumption, as well as the improving refining pattern in the country-wide oil refineries, do also have some contributions to the lower level of GHG emissions in the policies-in-hand scenario. Furthermore, increasing demand for natural gas in the final energy level will decrease GHG emissions over the model time horizon in both scenarios.

3.5. Carbon tax and renewables

Technology learning cost effects of solar PV, CSP, wind, and geothermal power generation did not work in either one of the scenarios. In other words, renewables could not compete with fossil-fueled power plants in the proposed scenarios. Since the model behaves based on a cost rational, the installed power generation capacity mix could be changed in the presence of carbon tax as a proxy for the externalities of using fossil fuels. Other policies including renewable portfolios, feed-in-tariffs, subsidies, promoting the distributed generation, and renewable auctions may have similar impacts.

Looking for a carbon tax floor that makes renewables competitive in a developing country rich in fossil fuels seems remarkable. Moreover, global studies show that the world will likely warm 3° Celsius, well above the agreed limit in Paris, if all the parties of the Agreement fully achieve their initially determined contributions [82]. Then, more ambitious contributions are needed in the short-term. Otherwise, carbon lock-in may occur in the energy system, which will need substantially costly transformation to comply with the 1.5–2° Celsius limit of the Paris Agreement goals [9,32]. Accordingly, Iran should propose successive contributions representing a progression beyond the initial ones. The current study addresses the idea by applying a carbon tax as regards utilizing more renewables.

The research findings show that a carbon price of $15,10 per ton lets the installation of 3900 MW of PV power plants in total from the latest period of the model time horizon. Then, the carbon tax threshold to make renewables competitive in Iran is around $15 per ton. For prices lower than the threshold amount, the model encourages early decommissioning of less efficient fossil-fueled power plants and more power generation from the combined cycle power plants.

While the marginal (discounted) distributed electricity price in the policies-in-hand scenario follows a decreasing trend from 35 to 29 US$ per MWh over the model time horizon, introducing a carbon tax $15,10 per ton will have a minimal effect on marginal prices (less than 4% increase). However, higher carbon tax (as much as $159 per ton), which induces early utilization of renewable power from 2021, increases the marginal electricity price significantly to 39 US$ per MWh in the 2016–2020 period. Considering the guaranteed power purchase policy introduced by the Iranian government to boost renewable power generation, the study result is quite comparable to the feed-in tariff for renewables.

4. Conclusions and policy implications

Meeting the growing demand for energy in a cost-effective and environmentally responsible manner is the first and foremost challenge of energy policymaking in Iran. The current study presented insights into the future energy demand and supply as well as how Iran may successfully contribute to the international efforts to halt global mean temperature increase regarding the initial contributions within the context of the Paris Climate Agreement.

According to the model results over the time horizon of 2016–2030, the most promising choices to grasp the maximum energy saving and emissions reduction in the supply-side of Iran's energy system are energy efficiency improvement measures including new capacity development of combined cycle power plants, repowering of the existing gas turbine power plants, gas flaring and leakage reduction, reducing power transmission and distribution losses as well as improving the refining pattern of the domestic refineries to produce more gasoline. Meanwhile, improving the efficiency of fossil-fueled power plants to 46% by the 2026–2030 period (48% by 2030) besides curbing routine gas flaring up to 90% could well cover the Iranian unconditional and conditional contributions to cut GHG emissions by 12% compared to the business-as-usual pattern.

Regarding the main national policies and plans on higher gasoline yield, efficient power generation, and gas flaring reduction, the results in the policies-in-hand scenario were totally compliant with the national targets. In this way, Iran can undertake the Intended Nationally Determined Contributions (INDCs) in line with the national policies to reduce energy intensity; although, this is subject to frictionless technology transfer and also relaxing the international financing services toward the energy sector of Iran. In other words, economically optimal development of the energy system in Iran will also help the country to meet the intended contributions to the Paris Climate Agreement. Then, there are synergies between energy supply at the minimum cost and contributions to the global GHG mitigation efforts.

Furthermore, it is possible to propose more ambitious mitigation targets by approaching the utilization of renewable energy resources and also improving energy efficiency in energy demand-side. While early utilization of renewables seems to be costly, energy efficiency improvement measures in the demand-side could be promising. Analyzing the demand-side in detail will help to explore the long-term opportunities for low-carbon development of energy systems. For instance, intending the electrification of the transportation sector could completely change the investment portfolio in the energy sector. However, this type of analysis for developing countries such as Iran lacks sufficient reliable data on both technologies and consumer behavior. Moreover, proposing more ambitious contributions within an extended modeling horizon of 2020–2100 will help to evaluate deep decarbonization, especially in the transportation and industry sectors. In this timeframe, it would be beneficial to analyze how the current and future contributions from Iran comply with the overall goal of limiting global average temperature increase to well below 2° Celsius or even 1.5° Celsius. This will be possible by introducing carbon budgets to the model based on the common effort-sharing approaches.

Authorship Contribution Statement

Hesam Ghadaksaz: Data curation, Database Preparation for Model, Running the Model, Writing - original draft, Investigation. **Yadollah Saboohi:** Conceptualization, Methodology, Supervision, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

Authors would like to thank both the International Institute for Applied Systems Analysis (IIASA) and the Iranian National Science Foundation (INSF) for conducting the researcher transfer program. The financial support of INSF to the present research work is well acknowledged. The authors would also offer special thanks to Dr. Keywan Riahi and Dr. Volker Krey of the IIASA Energy Program for their technical assistance. We are also grateful to the anonymous referees for their helpful comments and suggestions.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esr.2020.100541.

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